Search for microscopic black holes in pp collisions at $\sqrt{s} = 7TeV$

CMS Collaboration ; Chatrchyan, S ; Khachatryan, V ; Aguiló, E ; Amsler, C ; Chiochia, V ; De Visscher, S ; Favaro, C ; Ivova Rikova, M ; Millan Mejias, B ; Otiougova, P ; Robmann, P ; Snoek, H ; Verzetti, M ; et al

Abstract: A search for microscopic black holes in pp collisions at a center-of-mass energy of 7 TeV is presented. The data sample corresponds to an integrated luminosity of 4.7 fb−1 recorded by the CMS experiment at the LHC in 2011. Events with large total transverse energy have been analyzed for the presence of multiple energetic jets, leptons, and photons, which are typical signals of evaporating semiclassical and quantum black holes, and string balls. Agreement with the expected standard model backgrounds, which are dominated by QCD multijet production, has been observed for various combined multiplicities of jets and other reconstructed objects in the final state. Model-independent limits are set on new physics processes producing high-multiplicity, energetic final states. In addition, new model-specific indicative limits are set excluding semiclassical and quantum black holes with masses below 3.8 to 5.3 TeV and string balls with masses below 4.6 to 4.8 TeV . The analysis has a substantially increased sensitivity compared to previous searches.

DOI: https://doi.org/10.1007/JHEP04(2012)061

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP/2012-045
2013/01/24

CMS-EXO-11-071

Search for microscopic black holes in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

The CMS Collaboration*

Abstract

A search for microscopic black holes in pp collisions at a center-of-mass energy of 7 TeV is presented. The data sample corresponds to an integrated luminosity of $4.7\,\text{fb}^{-1}$ recorded by the CMS experiment at the LHC in 2011. Events with large total transverse energy have been analyzed for the presence of multiple energetic jets, leptons, and photons, which are typical signals of evaporating semiclassical and quantum black holes, and string balls. Agreement with the expected standard model backgrounds, which are dominated by QCD multijet production, has been observed for various combined multiplicities of jets and other reconstructed objects in the final state. Model-independent limits are set on new physics processes producing high-multiplicity, energetic final states. In addition, new model-specific indicative limits are set excluding semiclassical and quantum black holes with masses below 3.8 to 5.3 TeV and string balls with masses below 4.6 to 4.8 TeV. The analysis has a substantially increased sensitivity compared to previous searches.

Submitted to the Journal of High Energy Physics

*See Appendix A for the list of collaboration members

1 Introduction

One of the most spectacular predictions of theories with low-scale quantum gravity is the possibility of microscopic black hole (BH) production in proton-proton collisions at the high energies offered by the Large Hadron Collider (LHC) [1, 2]. Such models are motivated mainly by the puzzling large difference between the electroweak scale ($\sim$0.1 TeV) and the Planck scale ($M_{\mathrm{Pl}} \sim 10^{16}$ TeV), known as the hierarchy problem. In this analysis, we focus on black hole production in a model with n large, flat, extra spatial dimensions (ADD model) [3, 4]. In this and in other models, the fundamental scale of new physics in n extra dimensions is given in terms of a multidimensional Planck scale M_D, such that $M_D^{n+2} \propto M_{\mathrm{Pl}}^2 R^{-n}$, where R is the size of extra dimensions. Some of the conclusions also apply to black holes in the Randall–Sundrum model [5, 6], with a single warped extra dimension.

This analysis extends a previous search [7] for short-lived microscopic black holes carried out by the Compact Muon Solenoid (CMS) Collaboration in 2010. The present search is based on the full 2011 data sample, which corresponds to an integrated luminosity of $4.7 \pm 0.2\,\mathrm{fb}^{-1}$ [8, 9] at a center-of-mass energy of 7 TeV. The details of the analysis method and the underlying theory, as well as the detailed description of black hole evaporation models, can be found in the original publication [7]. Typically, microscopic black holes are characterized by the production of a large number of energetic final-state particles, 75% of which are jets. Searches for black holes have also been performed by the ATLAS Collaboration [10, 11].

We present our results in terms of model-independent limits on the cross section times the branching fraction into a multiparticle final state. Further, we interpret the results in terms of a set of benchmark black hole models. The analysis also extends the previous CMS search for semiclassical black holes to probe for other quantum gravity objects such as string balls [12] and quantum black holes [13]. It is commonly accepted that the semiclassical approximation is valid when the black hole mass is some 3–5 times larger than the M_D. The string balls are hypothetical precursors of semiclassical black holes in an extreme quantum limit, when the mass of the object is close to the Planck scale. In cases where the semiclassical approximation no longer holds, string balls may offer a more realistic description of black hole formation and decay. String balls are described by the string scale M_S and string coupling g_S. These objects would evaporate similarly to black holes, except that the evaporation would occur at the Hagedorn temperature, which does not depend on the string-ball mass [12, 14], unlike the Hawking temperature [15], which decreases as the black hole mass increases. Another possibility is that a light black hole with mass close to the Planck scale may evaporate faster than it thermalizes, resulting predominantly in a nonthermal decay into a pair of jets, rather than into high-multiplicity final states [13, 16, 17]. We search for production of these objects, referred to as quantum black holes, and for their decay in both the ADD scenario and in the Randall–Sundrum model of low-scale gravity with a single ($n = 1$) compact extra dimension.

2 The CMS detector

A detailed description of the CMS experiment can be found elsewhere [18]. The CMS detector consists of a 3.8 T superconducting solenoid enclosing a silicon pixel and strip tracker, a crystal electromagnetic calorimeter (ECAL), and a brass-scintillator hadronic calorimeter (HCAL). The finely segmented ECAL employs lead-tungstate crystals with transverse dimensions: $\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$. The HCAL cells are grouped in projective towers, of granularity $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ at central rapidities and increasing progressively in the forward region. Here, ϕ and θ are the azimuthal and polar angles, with θ measured with respect to the direction of the counterclockwise beam. The pseudorapidity η is defined as $-\ln[\tan(\theta/2)]$. Muons are measured in the pseudorapidity range $|\eta| < 2.4$ in gas-ionization detectors embedded in the steel return yoke.

The CMS trigger system, used to select the most interesting events, consists of two levels. A first level (L1), composed of custom electronics, uses information from the calorimeters and muon detectors to decrease the event rate to 80 kHz. A software-based High Level Trigger (HLT) further decreases the event rate to 350–400 Hz for data storage.

As in the previous analysis, we use data collected with a suite of H_T triggers, where H_T is defined as a scalar sum of the transverse energies (E_T) of the jets above a threshold.[1] There have been changes introduced in the trigger logic both at L1 and HLT since 2010. We now use jets corrected for the calorimeter response to calculate the H_T variable at the HLT (uncorrected jets are still used at L1). Also, the minimum H_T thresholds, as well as the minimum jet E_T requirement for a jet to be counted towards H_T, have been increased to account for pileup effects and to allow for the increased instantaneous luminosity of the LHC. This minimum jet E_T threshold is 10 GeV at L1, and 40 GeV at the HLT. The minimum H_T threshold at the HLT varies between 350 and 650 GeV, depending on the instantaneous luminosity. Only jets reconstructed at central pseudorapidities $|\eta| < 3.0$ are used in the H_T calculations at L1 and at the HLT for the 2011 data-taking period. The trigger is fully efficient for events with H_T above 800 GeV. In order to explore all possible black hole decay modes, the entire analysis was also repeated using data collected with multimuon or missing transverse energy (E_T^{miss}) triggers, but this yielded no events consistent with the expected black hole production.

3 Event reconstruction and Monte Carlo samples

Jets are reconstructed offline using energy deposits in the HCAL and ECAL, which are clustered using an infrared-safe anti-k_T algorithm with a distance parameter of 0.5 [19–21]. Quality criteria are applied to jets in order to remove calorimeter noise and noncollision background [22]. We require jets to have $E_T > 20$ GeV and to be reconstructed within $|\eta| < 2.6$. Further, jet energies are corrected for calorimeter nonuniform response with correction factors derived from Monte Carlo (MC) simulation and dijet events from collision data [22]. The transverse energy resolution for jets $\Delta E_T/E_T$ is better than 15% in the range considered. We reconstruct E_T^{miss} as the modulus of the negative vector sum of transverse energies in the individual calorimeter towers and is further corrected for the jet energy scale and for muon momenta measured in the trackers [23].

Electrons and photons are reconstructed as isolated energy deposits in the ECAL with a shape consistent with that expected for electromagnetic showers. Electrons are required to have a track matched to the calorimeter cluster, while photons are required to have no matching hits in the silicon layers. Electrons and photons are selected with $E_T > 20$ GeV and are required to be reconstructed in the fiducial barrel ($|\eta| < 1.44$) or endcap ($1.56 < |\eta| < 2.4$) regions. The ECAL has excellent energy resolution, for example contributing 1 GeV to the observed width of the Z boson using e^+e^- pairs with low bremsstrahlung loss, measured in the barrel region [24].

Muons are reconstructed as matched tracks in the muon spectrometer and the silicon tracker. Muons are selected with $|\eta| < 2.1$ and $p_T > 20$ GeV, and are required to be isolated from other tracks. Requiring the muons to have distance of the closest approach < 0.2 cm helps to suppress backgrounds from cosmic-ray muons. Here, the distance of the closest approach is defined as the shortest distance between the beam line and the direction of an object in the

[1] Energetic electrons and photons are also reconstructed as jets at the trigger level.

transverse plane. Performing a combined fit to the track segments measured in the silicon tracker and the muon system results in a transverse momentum resolution between 1% and 5% for p_{T} values up to 1 TeV. The minimum separation between any two objects (jet, lepton, or photon) is required to be $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} > 0.5$.

Simulated samples of semiclassical black hole events are produced using a parton-level BLACKMAX [25] (v2.01) and CHARYBDIS [26, 27] (CHARYBDIS 2, v1.0.3) MC generators, followed by the parton showering simulation with PYTHIA [28] (v6.420), and a fast parametric simulation of the CMS detector [29]. The MSTW2008lo68cl [30] parton distribution functions (PDF) are used for generating the signal samples. The BLACKMAX and CHARYBDIS generators calculate the total cross section σ from geometric considerations, assuming that $\sigma \propto \pi r_S^2$, where r_S is the Schwarzschild radius [1, 2]. The BLACKMAX generator uses the approximation of rotating black holes, which includes an additional factor that depends on the number of extra dimensions n. The CHARYBDIS generator incorporates a more detailed model based on Yoshino–Rychkov corrections [31, 32] to the pure geometrical cross section, resulting in production cross sections that are lower by a factor of $1.36, 1.59$, and 1.78 compared to those from BLACKMAX for $n = 2, 4$, and 6, respectively. These scale factors can be used to interpret the results obtained with one framework in terms of the other.

Certain models are supported by both generators: rotating and nonrotating black holes, and black holes with mass and angular momentum loss prior to evaporation. This loss is set to be 10% in the BLACKMAX generator, while it is estimated in the Yoshino–Rychkov model and varies from 18% to 30% for $n = 2$ to 6 in the CHARYBDIS generator. In addition, we use CHARYBDIS to simulate black hole evaporation resulting in a stable remnant with mass equal to the multidimensional Planck scale M_D, or a boiling remnant (unique to the CHARYBDIS generator). Both of these scenarios represent alternative descriptions of the final stage of the black hole evolution. In the case of a stable remnant, the terminal stage of a black hole is a noninteracting remnant with a mass of order M_D; in the case of a boiling remnant, a black hole undergoes a transformation into a string ball at a mass close to M_D with subsequent evaporation at a fixed temperature. We produce a number of string-ball samples using the BLACKMAX generator. Finally, the QBH (version 1.03) matrix-element generator [33] with CTEQ6L PDF set [34] is used, followed by the parton showering simulation with PYTHIA and fast simulation of the CMS detector, to produce quantum black hole samples. Table 1 summarizes the models used in this search.

Table 1: Signal Monte Carlo samples and generators used in the analysis.

Sample description	BLACKMAX	CHARYBDIS	QBH
nonrotating BH	YES	YES	NO
Rotating BH	YES	YES	NO
Rotating BH with mass and angular momentum loss	YES (10% loss)	YES ($18-30$% loss)	NO
Rotating BH, low multiplicity regime	NO	YES	NO
Boiling remnant	NO	YES	NO
Stable remnant	NO	YES	NO
String balls	YES	NO	NO
Quantum BH	NO	NO	YES

4 Analysis method

The total transverse energy is used to separate black hole candidate events from backgrounds. A variable S_{T} is defined as a scalar sum of the transverse energy (E_{T}) of individual objects: jets, electrons, photons, and muons passing the selections described above. Only objects with $E_{\mathrm{T}} > 50\,\mathrm{GeV}$ enter into the sum for the calculation of S_{T} and count towards the final-state multiplicity N. This rather high minimum transverse energy requirement makes the analysis insensitive to the jets from pileup and reduces the SM backgrounds by a few orders of magnitude, while being fully efficient for black hole decays. We further add the measured $E_{\mathrm{T}}^{\mathrm{miss}}$ in the event to the S_{T}, if $E_{\mathrm{T}}^{\mathrm{miss}} > 50\,\mathrm{GeV}$. Generalization of the S_{T} definition to include $E_{\mathrm{T}}^{\mathrm{miss}}$ is important for testing black hole models with a significant amount of missing energy such as models with a stable noninteracting remnant. A spurious $E_{\mathrm{T}}^{\mathrm{miss}}$ may arise in an event as the result of mismeasurement of the jets. However, we have checked that the consequent effect on S_{T} of double counting energy in both the jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ contributions is negligible. Note that by construction, particle misidentification does not affect the total transverse energy in the event considerably.

Depending on the details of the black hole evaporation, a large variation of particle multiplicity in the final state, and a large range of missing transverse energies are possible. While resulting in quite different signatures, these variations typically have very little effect on the value of S_{T} in the event. A recent work on quantum-gravity black holes [35] also suggests a larger number of softer particles produced in black hole evaporation than in the semiclassical case, further emphasizing the importance of S_{T} as a largely model-independent variable for black hole searches.

The main background to black hole production arises from QCD multijet production, which dominates the event rates at large S_{T}. Smaller backgrounds come from γ/W/Z+jets and $\mathrm{t\bar{t}}$ production. These smaller backgrounds are negligible at large values of S_{T} and contribute less than 1% to the total background after the final selection. We estimate their contribution from MC simulation, using the MADGRAPH [36] leading-order parton-level event generator (with up to three extra partons included in the simulation) with the CTEQ6L PDF set followed by PYTHIA [28] parton showering and full CMS detector simulation via GEANT4 [37]. For the dominant QCD background, however, we estimate backgrounds from the observed data using the S_{T} multiplicity invariance method [7]. This method relies on the independence of the shape of the S_{T} spectrum on the number of final-state objects N; an empirical observation extensively checked by using various MC samples (ALPGEN and PYTHIA) as well as low-multiplicity data. The origin of this invariance lies in the collinear nature of the final-state radiation, which typically does not change the total transverse energy in the event; hence the independence of the S_{T} spectrum of the jet multiplicity for the QCD background. This invariance allows us to predict the shape of the S_{T} spectrum for any number of objects using the dijet data, which has been studied extensively for presence of new physics in dedicated analyses [38–40].

We use low-multiplicity data with $N = 2$ and $N = 3$ to obtain the background shape by fitting the S_{T} distributions between 1200 and 2800 GeV with the ansatz function $P_0(1+x)^{P_1}/x^{P_2+P_3\log(x)}$, which is shown in Fig. 1 as a solid line. No evidence of new physics has been observed in this region in a dedicated analysis [38]. To estimate the systematic uncertainty of the method, the same S_{T} distributions are fitted with two additional functions, $P_0/(P_1+P_2x+x^2)^{P_3}$ and $P_0/(P_1+x)^{P_2}$. Thus, an envelope of functions is formed (shown as the shaded area in Fig. 1) and is used as the systematic uncertainty.

Figure 2 shows the fit result of the background prediction for the inclusive samples with high object multiplicity events. Here, the shape of the S_{T} distribution obtained from the $N = 2$

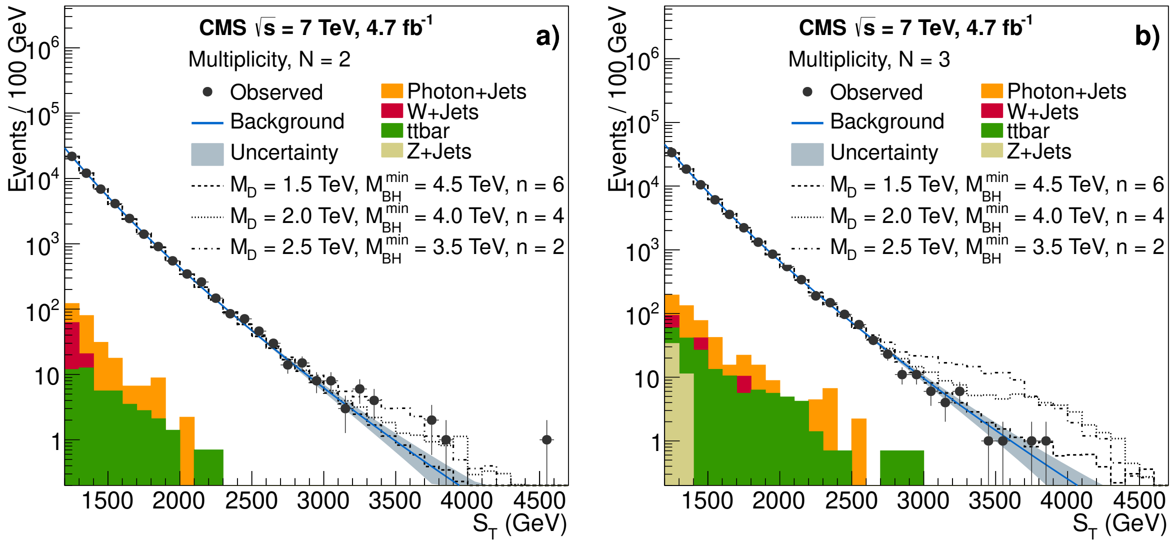

Figure 1: Distribution of the total transverse energy, S_T, for low-multiplicity events with multiplicity: a) $N = 2$ and b) $N = 3$ photons, electrons, muons, or jets in the final state. Observed data are depicted as points with error bars; solid line with a shaded band is the background prediction and its systematic uncertainty. Non-QCD backgrounds are shown as filled histograms (not stacked). Also shown is the black hole signal for three parameter sets of the BLACKMAX nonrotating black hole model, demonstrating that signal contamination in the fit region of $1200 - 2800$ GeV would be small.

sample is normalized to the observed data in the range 1800 to 2200 GeV, where no signal contribution is expected. Also shown are the expected semiclassical black hole signals for three parameter sets of the BLACKMAX nonrotating black hole model. The results are presented separately for six different values of the minimum final state multiplicity. The data agree with the background shapes from the low-multiplicity samples and do not exhibit evidence for new physics. Figure 3 shows a similar comparison of the experimental S_T distribution with the predicted signal for three parameter sets of the QBH quantum black hole model. In this case the comparison is shown separately for just two values of the minimum final state multiplicity, reflecting the different decay characteristics expected for quantum black holes compared to semiclassical black holes.

5 Results

In order to set exclusion limits on black hole production, we assign systematic uncertainties on the background estimate varying from 3% to 300% in the S_T range used in this search. These uncertainties are dominated by the uncertainties from using various fit ansatz functions (2%–300%), which are added in quadrature to the second-largest contribution, which arise from the normalization statistical uncertainty (2%–21%). The integrated luminosity is measured with 4.5% uncertainty [8, 9] utilizing information from the forward calorimeters. The signal uncertainty is dominated by the jet energy scale uncertainty of $\approx 2\%$ [22], which translates into 2% uncertainty on the signal. An additional 2% uncertainty on the signal acceptance comes from the variation of acceptance obtained with the default MSTW2008lo68cl PDF library and PDFs within the CTEQ61 and CTEQ66 error sets [34].

Given the significant model dependence of the black hole production cross section and decay patterns, it is not practical to test all different variations of model parameters, offered by recent

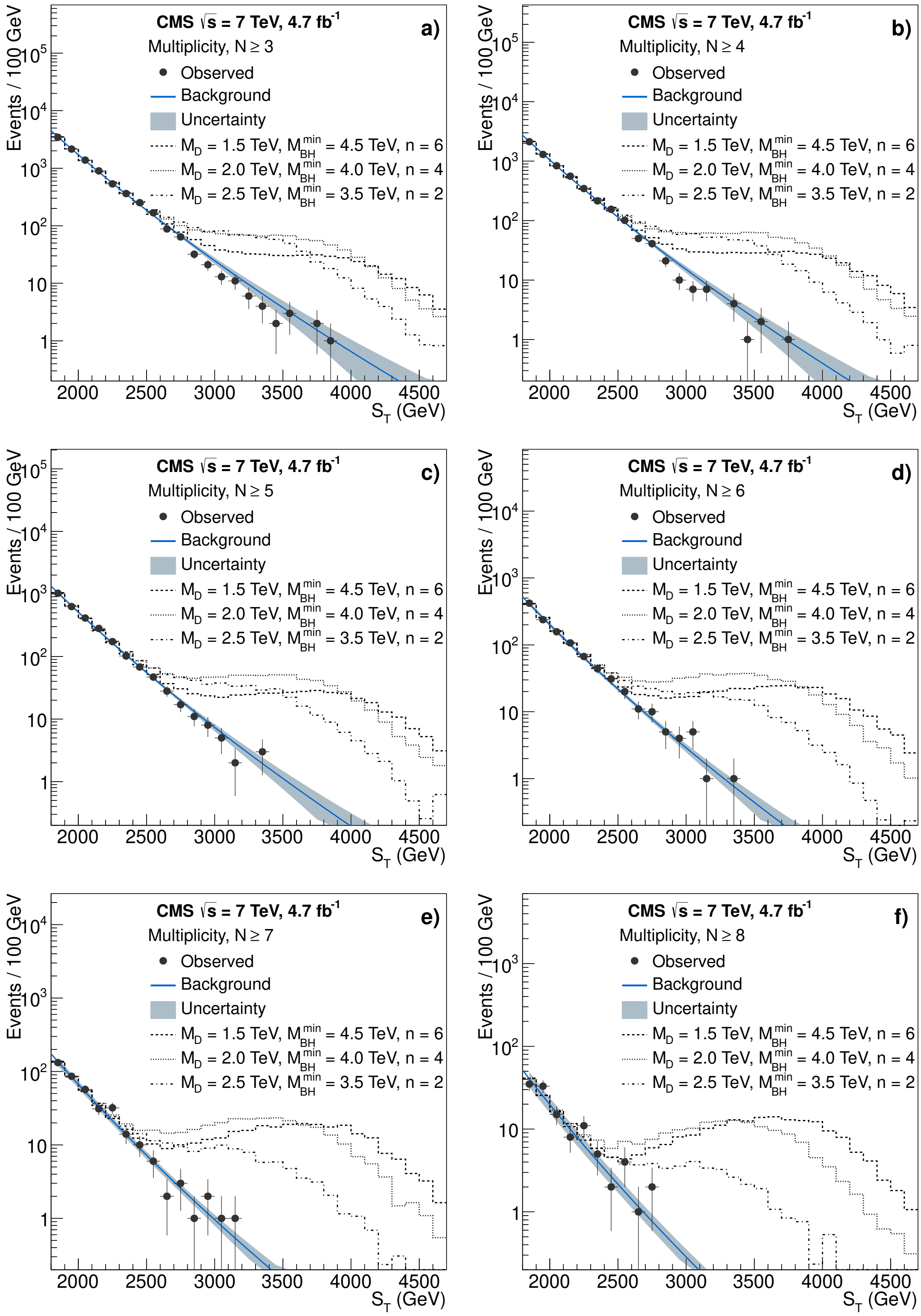

Figure 2: Distribution of the total transverse energy, S_T, for events with multiplicity: a) $N \geq 3$, b) $N \geq 4$, c) $N \geq 5$, d) $N \geq 6$, e) $N \geq 7$, and f) $N \geq 8$ objects (photons, electrons, muons, or jets) in the final state. Observed data are depicted as points with error bars; the solid line with a shaded band is the background prediction and its systematic uncertainty. Also shown are the expected semiclassical black hole signals for three parameter sets of the BLACKMAX nonrotating black hole model. Here, M_{BH}^{min} is the minimum black hole mass, M_D is the multidimensional Planck scale, and n is the number of extra dimensions.

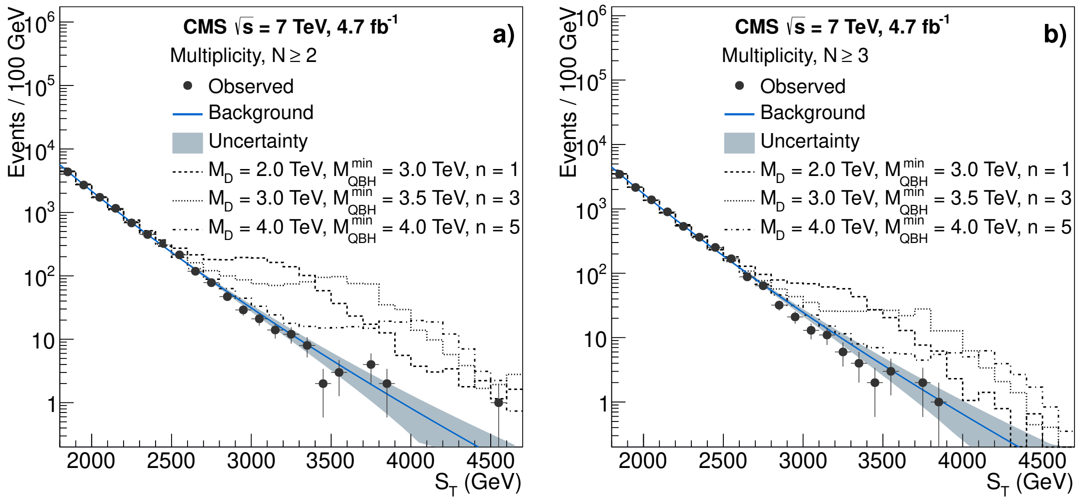

Figure 3: Distribution of the total transverse energy, S_{T}, for events with multiplicity: a) $N \geq 2$ and b) $N \geq 3$ objects in the final state. Observed data are depicted as points with error bars; the solid line with a shaded band is the background prediction and its systematic uncertainty. Also shown are the expected quantum black hole signals for three parameter sets. Here, $M_{\mathrm{QBH}}^{\mathrm{min}}$ is the minimum quantum black hole mass, M_D is the multidimensional Planck scale, and n is the number of extra dimensions.

black hole event generators, in a dedicated search. This study considers some 700 different signal MC samples, yet it does not come close to spanning the entire parameter space of the models; scaling the number of signal samples up and presenting the results for every model therefore becomes impractical. Hence, we first present the results of our search in a generic, model-independent way, which would allow others to probe additional models using parton-level MC information, possibly augmented with a very basic detector simulation. To facilitate such an approach, we provide model-independent limits on the cross section times the acceptance for new physics production in high-S_{T} inclusive final states for $N \geq 3, 4, 5, 6, 7$, and 8. The limits are set using a modified frequentist $\mathrm{CL_s}$ method [41, 42] with log-normal prior used to marginalize nuisance parameters in the likelihood function.

Figure 4 shows 95% confidence level (CL) limits from a counting experiment placed on the experimentally reconstructed value $S_{\mathrm{T}} > S_{\mathrm{T}}^{\mathrm{min}}$ as a function of $S_{\mathrm{T}}^{\mathrm{min}}$, which can be used to test models of new physics that result in these final states, including (but not limited to) an even broader variety of black hole models than we covered in this analysis. The 95% CL limits from 2010 data [7] are also shown in Fig. 4 for comparison. The present model-independent limits are roughly 0.6 fb for high values of S_{T}, representing a two orders of magnitude improvement over the limits reported in our first publication [7]. Given the higher statistics of the 2011 sample, we are also able to extend these limits to the $N \geq 6, 7$, and 8 cases.

For a specific subset of the black hole models [7] that are being probed, we also set dedicated limits on semiclassical and quantum black hole and string-ball production performing counting experiments using optimized S_{T} and N selections. It should be noted that the semiclassical approximation used for deriving the cross section within respective benchmark scenarios is expected to break down for many of the points probed, a point emphasized in a recent critique [43]. Thus, these limits should be treated as indicative, rather than precise.

The signal (S) significance is optimized in the presence of background (B) using a test statistic $S/\sqrt{S+B}$ for each set of model parameters. The optimum choices of S_{T} and N for a few

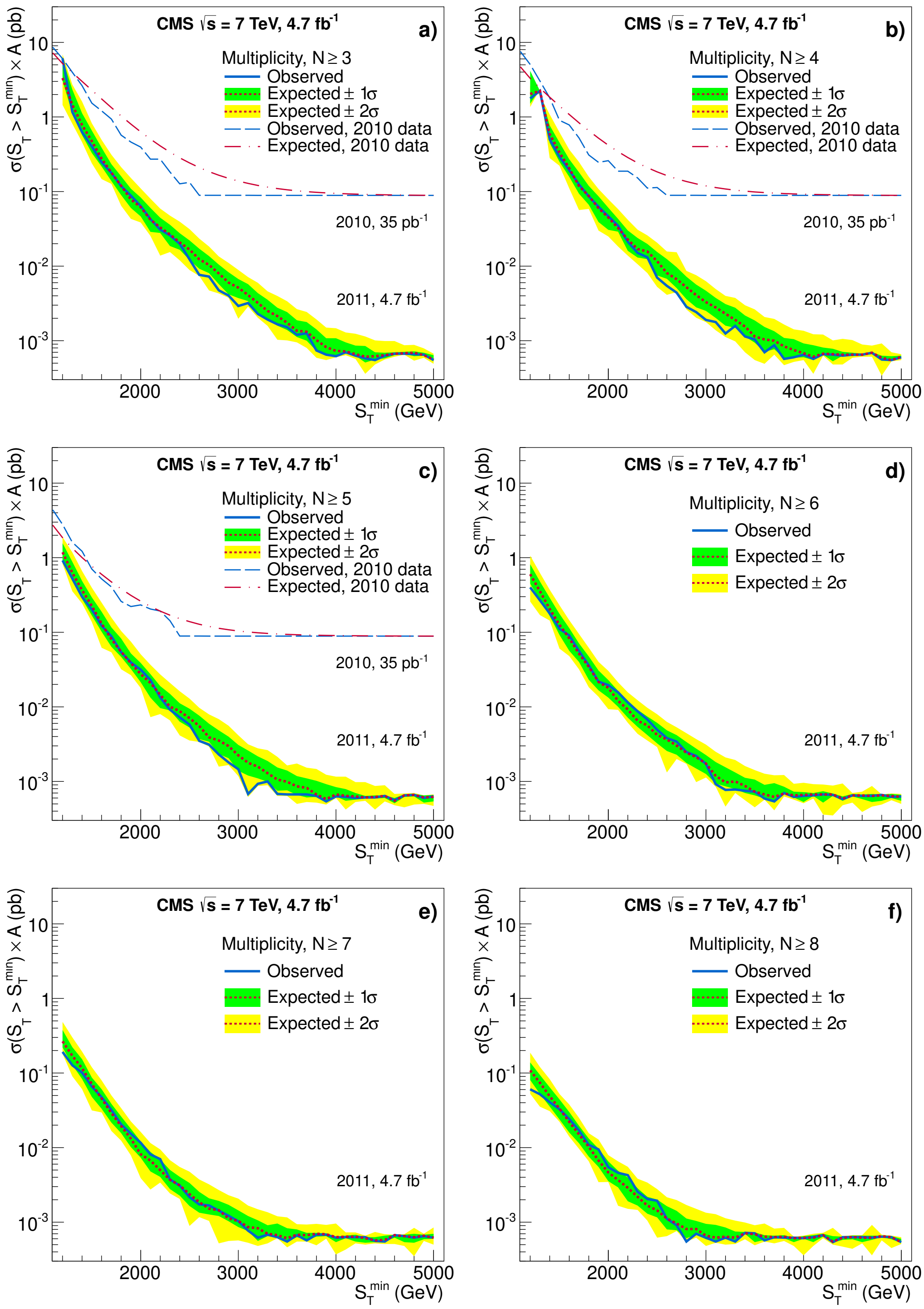

Figure 4: Model-independent 95% CL upper cross section limits for counting experiments with $S_{\mathrm{T}} > S_{\mathrm{T}}^{\mathrm{min}}$ as a function of $S_{\mathrm{T}}^{\mathrm{min}}$ for events with multiplicity: a) $N \geq 3$, b) $N \geq 4$, c) $N \geq 5$, d) $N \geq 6$, e) $N \geq 7$, and f) $N \geq 8$. The blue solid (red dotted) lines correspond to an observed (expected) limit for nominal signal acceptance uncertainty of 5%, compared to observed (expected) limits obtained with 2010 CMS data and shown as blue dashed (red dash-dotted) line. The green and yellow bands represent one and two standard deviations from the expected limits.

illustrative benchmark scenarios are listed in Table 2, as well as the predicted number of background events, expected number of signal events, and the observed number of events in data. The corresponding cross section limits at the 95% CL from the counting experiments are shown in Fig. 5 for a small subset of characteristic signal points.

Table 2: Details of some of the BLACKMAX nonrotating black hole model parameters probed in the analysis. Shown are: multidimensional Planck scale (M_D), minimum black hole mass (M_{BH}), number of extra dimensions (n), corresponding leading order cross sections (σ), and optimal selections on the minimum decay multiplicity ($N \geq N^{\mathrm{min}}$) and minimum S_{T}, as well as signal acceptance (A), expected number of signal events (N^{sig}), number of observed events in data (N^{data}), expected background (N^{bkg}) with its systematic uncertainty, and observed (σ^{95}) and expected ($\langle\sigma^{95}\rangle$) limit on the signal at 95% CL.

M_D (TeV)	M_{BH} (TeV)	n	σ (pb)	N^{min}	$S_{\mathrm{T}}^{\mathrm{min}}$ (TeV)	A (%)	N^{sig}	N^{data}	N^{bkg}	σ^{95} (pb)	$\langle\sigma^{95}\rangle$ (pb)
1.5	3.0	6	26	3	1.9	88.0	110000	5999	5970 ± 180	0.092	0.091
1.5	3.5	6	5.0	3	2.2	88.0	21000	1565	1590 ± 66	0.035	0.06
1.5	4.0	6	0.77	4	2.5	85.8	3100	245	280 ± 24	0.0087	0.014
1.5	4.5	6	0.091	5	2.8	81.8	350	29	42 ± 7	0.0028	0.0044
1.5	5.0	6	0.0071	6	3.2	73.5	25	1	3.7 ± 1.3	0.0012	0.0015
1.5	5.5	6	0.0003	7	3.7	61.8	0.82	0	0.21 ± 0.14	0.0011	0.0011
2.0	3.0	4	6.5	3	2.0	82.5	25000	3847	3810 ± 120	0.077	0.075
2.0	3.5	4	1.3	3	2.4	79.7	4700	667	690 ± 45	0.025	0.026
2.0	4.0	4	0.20	3	2.8	77.1	720	95	140 ± 23	0.0054	0.0094
2.0	4.5	4	0.024	4	3.2	69.5	77	8	19 ± 6	0.0017	0.0032
2.0	5.0	4	0.0018	5	3.6	61.3	5.2	0	2.3 ± 1.3	0.0011	0.0014
2.5	3.0	2	0.97	3	2.4	62.3	2800	667	690 ± 45	0.031	0.034
2.5	3.5	2	0.19	3	2.7	65.3	590	159	210 ± 28	0.0098	0.016
2.5	4.0	2	0.031	3	3.2	57.7	85	18	31 ± 11	0.0039	0.0054
2.5	4.5	2	0.0039	4	3.6	46.7	8.5	1	4.6 ± 2.7	0.0017	0.0024
2.5	5.0	2	0.0003	4	4.1	41.3	0.59	0	$0.86^{+0.89}_{-0.86}$	0.0016	0.0017

By translating the cross section limits into ADD model expectations, we can exclude the production of semiclassical black holes with a minimum mass varying from 3.9 to 5.3 TeV for values of the multidimensional Planck scale $M_D \leq 4$ TeV and a number of extra dimensions $n \leq 6$ at 95% CL (see Fig. 6). The excluded minimum masses of quantum black holes are in the 3.8–5.2 TeV range for M_D up to 4 TeV and are shown in Fig. 7. The 95% CL limits on the string-ball production cross section as a function of the minimum mass of the string ball are shown in Fig. 8. We exclude string-ball production with a minimum mass from 4.6 to 4.8 TeV, depending on the model. Despite the caveats mentioned above, we consider it useful to present these results, since at present there are no alternative quantitative calculations in the regime where the semiclassical approximation breaks down. Furthermore, although the predicted cross section is very sensitive to changes in the model of black hole production and decay, varying the model assumptions results in only moderate changes to the mass limit, because of the exponential dependence of the cross section on the black hole mass. Nontheless, we emphasize that the model-independent limits set in this Letter should be used in the regime when the semiclassical approximation fails in order to obtain more reliable predictions.

6 Conclusions

An update has been presented of an earlier dedicated search for black holes at the LHC [7] and new model-independent limits have been set on the production of energetic multiparticle

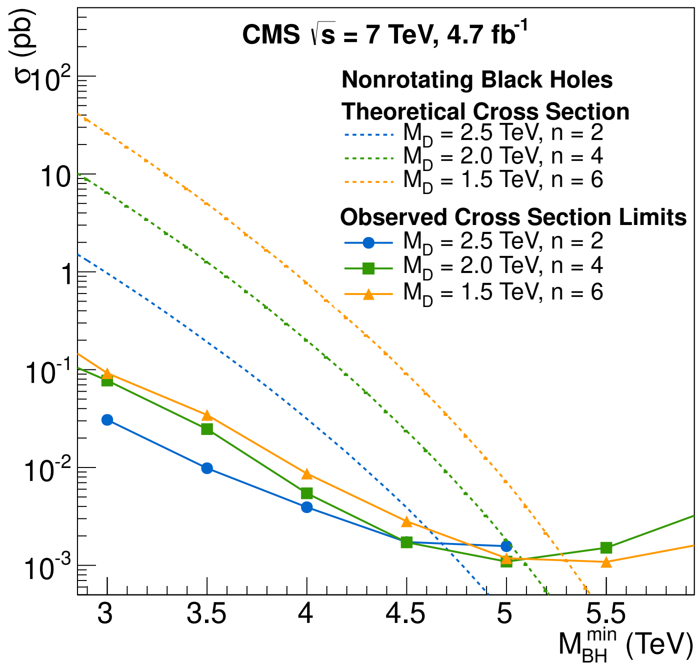

Figure 5: Cross section limits at 95% CL from the counting experiments optimized for various black hole parameter sets (solid lines) compared with signal production cross sections from the BLACKMAX generator (dashed lines) as a function of minimum black hole mass.

final states, which can be used to constrain a large variety of models of new physics. For the benchmark models, the following can be concluded from Fig. 6: (i) since the excluded masses of rotating and nonrotating black holes are similar, the effect of black hole spin on the sensitivity of the search is small; (ii) in case of energy/momentum loss due to gravitational radiation not trapped by the forming event horizon, the excluded black hole masses are ~10% lower than in the case of no losses; (iii) the choice of S_T as a discriminating variable makes the results largely insensitive to the details of the last stage of black holes evaporation, whether a stable remnant is formed or not. Numerically, the limits on the minimum semiclassical and quantum black hole and string-ball masses are in the range 3.8 to 5.3 TeV for a wide range of model parameters. These are the most restrictive limits on black hole production set at hadron colliders to date. Further extension of this search will be possible when the LHC energy is increased in the future.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC

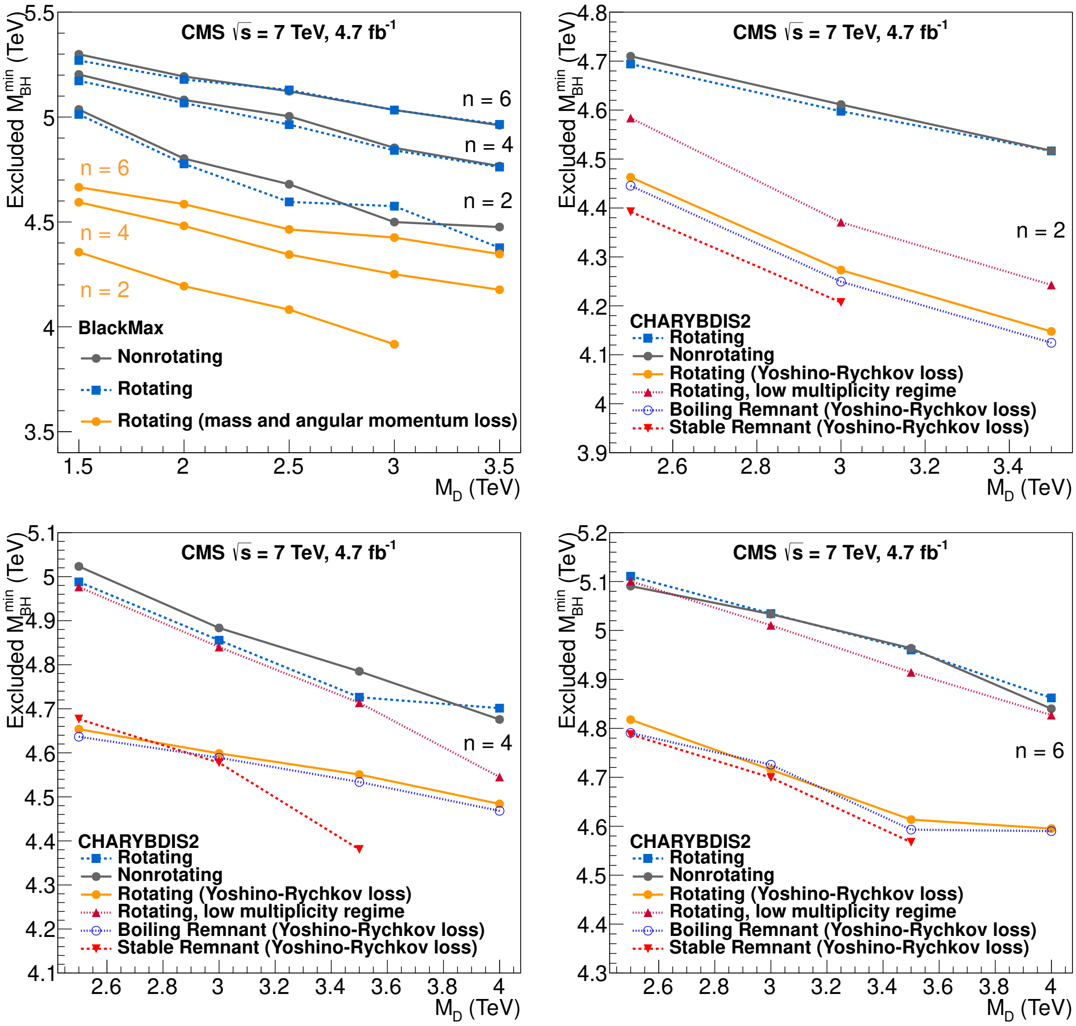

Figure 6: Minimum black hole mass excluded at 95% CL as function of the reduced Planck scale for various BLACKMAX black hole models without the stable remnant and number of extra dimensions of two, four, and six (Top left). The minimum black hole mass, excluded at 95% CL, as function of the reduced Planck scale for various CHARYBDIS black hole models with or without the stable remnant and number of extra dimensions n of (top right) two, (bottom left) four, and (bottom right) six. The areas below each curve are excluded by this search.

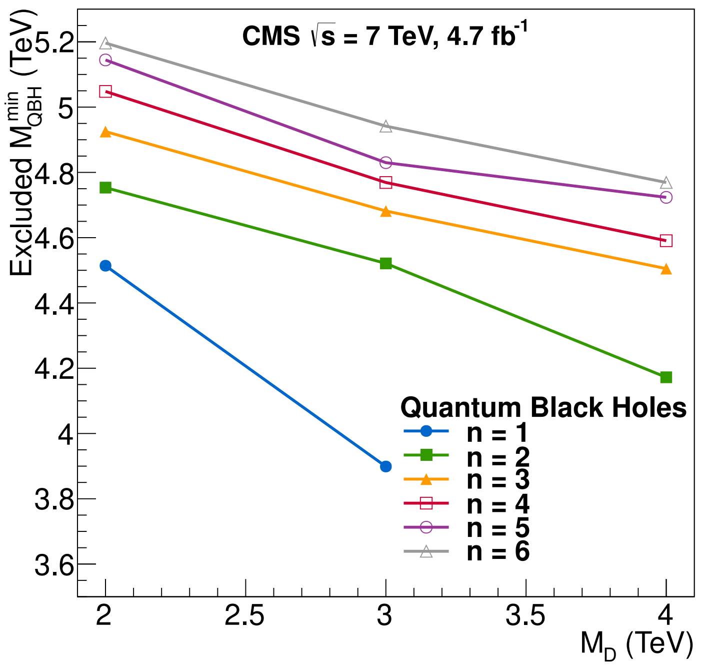

Figure 7: 95% CL excluded minimum quantum black hole mass as function of the reduced Planck scale for number of extra dimensions n of one (Randall–Sundrum model) and two to six (ADD model). This search excludes the areas below each curve.

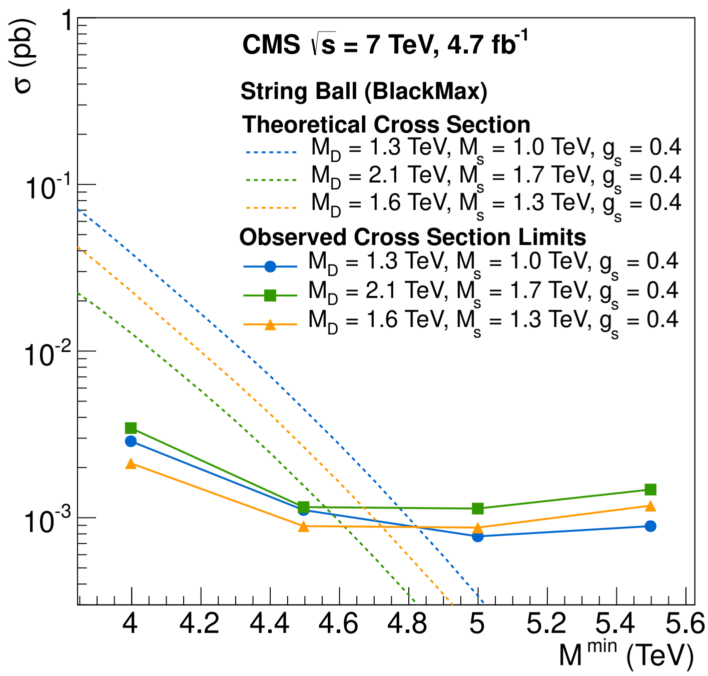

Figure 8: Cross section limits at 95% CL from the counting experiments optimized for various string-ball parameter sets (solid lines) compared with signal production cross section (dashed lines) as a function of minimum string-ball mass. Here, M_D is the multidimensional Planck scale, M_S is the string scale, and g_S is the string coupling.

(United Kingdom); DOE and NSF (USA).

References

[1] S. Dimopoulos and G. Landsberg, "Black Holes at the LHC", *Phys. Rev. Lett.* **87** (2001) 161602, doi:10.1103/PhysRevLett.87.161602, arXiv:hep-ph/0106295.

[2] S. Giddings and S. Thomas, "High-energy colliders as black hole factories: The end of short distance physics", *Phys. Rev. D* **65** (2002) 056010, doi:10.1103/PhysRevD.65.056010, arXiv:hep-ph/0106219.

[3] N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, "The hierarchy problem and new dimensions at a millimeter", *Phys. Lett. B* **429** (1998) 263–267, doi:10.1016/S0370-2693(98)00466-3, arXiv:hep-ph/9803315.

[4] N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, "Phenomenology, astrophysics and cosmology of theories with submillimeter dimensions and TeV scale quantum gravity", *Phys. Rev. D* **59** (1999) 086004, doi:10.1103/PhysRevD.59.086004, arXiv:hep-ph/9807344.

[5] L. Randall and R. Sundrum, "Large Mass Hierarchy from a Small Extra Dimension", *Phys. Rev. Lett.* **83** (1999) 3370–3373, doi:10.1103/PhysRevLett.83.3370, arXiv:hep-ph/9905221.

[6] L. Randall and R. Sundrum, "An Alternative to Compactification", *Phys. Rev. Lett.* **83** (1999) 4690–4693, doi:10.1103/PhysRevLett.83.4690, arXiv:hep-th/9906064.

[7] CMS Collaboration, "Search for microscopic black hole signatures at the Large Hadron Collider", *Phys. Lett. B* **697** (2011) 434–453, doi:10.1016/j.physletb.2011.02.032, arXiv:1012.3375.

[8] CMS Collaboration, "Measurement of CMS Luminosity", CMS Physics Analysis Summary CMS-PAS-EWK-10-004, (2010).

[9] CMS Collaboration, "Absolute Calibration of the CMS Luminosity Measurement: Summer 2011 Update", CMS Physics Analysis Summary CMS-PAS-EWK-11-001, (2011).

[10] ATLAS Collaboration, "Search for strong gravity signatures in same-sign dimuon final states using the ATLAS detector at the LHC", (2011). arXiv:1111.0080. Submitted to *Phys. Lett. B*.

[11] ATLAS Collaboration, "A search for new physics in dijet mass and angular distributions in pp collisions at $\sqrt{s} = 7$ TeV measured with the ATLAS Detector", *New J. Phys.* **13** (2011) 053044, doi:10.1088/1367-2630/13/5/053044, arXiv:1103.3864.

[12] S. Dimopoulos and R. Emparan, "String balls at the LHC and beyond", *Phys. Lett. B* **526** (2002) 393–398, doi:10.1016/S0370-2693(01)01525-8, arXiv:hep-ph/0108060.

[13] P. Meade and L. Randall, "Black holes and quantum gravity at the LHC", *JHEP* **05** (2008) 003, doi:10.1088/1126-6708/2008/05/003, arXiv:0708.3017.

[14] R. Hagedorn, "Statistical thermodynamics of strong interactions at high-energies", *Nuovo Cim. Suppl.* **3** (1965) 147–186.

[15] S. Hawking, "Particle Creation by Black Holes", *Commun. Math. Phys.* **43** (1975) 199–220, doi:10.1007/BF02345020.

[16] X. Calmet, W. Gong, and S. Hsu, "Colorful quantum black holes at the LHC", *Phys. Lett. B* **668** (2008) 20–23, doi:10.1016/j.physletb.2008.08.011, arXiv:0806.4605.

[17] D. Gingrich, "Quantum black holes with charge, colour, and spin at the LHC", *J. Phys. G* **37** (2010) 105108, doi:10.1088/0954-3899/37/10/105008, arXiv:0912.0826.

[18] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[19] M. Cacciari, G. Salam, and G. Soyez, "The anti-k_T jet clustering algorithm", *JHEP* **08** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

[20] M. Cacciari and G. P. Salam, "Dispelling the N^3 myth for the k_t jet-finder", *Phys. Lett. B* **641** (2006) 57–61.

[21] M. Cacciari, G. P. Salam, and G. Soyez, "FastJet user manual", (2011). arXiv:1111.6097.

[22] CMS Collaboration, "Determination of jet energy calibration and transverse momentum resolution in CMS", *JINST* **06** (2011) P11002, doi:10.1088/1748-0221/6/11/P11002, arXiv:1107.4277.

[23] CMS Collaboration, "Missing transverse energy performance of the CMS detector", *JINST* **06** (2011) P09001, doi:10.1088/1748-0221/6/09/P09001, arXiv:1106.5048.

[24] CMS Collaboration, "CMS ECAL performance on 2011 data", CMS Detector Performance Summary CMS-DP-2012-002, (2012).

[25] D.-C. Dai et al., "BLACKMAX: A black-hole event generator with rotation, recoil, split branes, and brane tension", *Phys. Rev. D* **77** (2008) 076007, doi:10.1103/PhysRevD.77.076007.

[26] C. Harris, P. Richardson, and B. Webber, "CHARYBDIS: A black hole event generator", *JHEP* **08** (2003) 033, doi:10.1088/1126-6708/2003/08/033, arXiv:hep-ph/0307305.

[27] J. Frost et al., "Phenomenology of production and decay of spinning extra-dimensional black holes at hadron colliders", *JHEP* **10** (2009) 014, doi:10.1088/1126-6708/2009/10/014, arXiv:0904.0979.

[28] T. Sjöstrand, S. Mrenna, and P. Skands, "PYTHIA 6.4 physics and manual", *JHEP* **05** (2006) 026, doi:10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.

[29] CMS CollaborationS. Abdullin, et al., "Fast simulation of the CMS detector at LHC", in *International Conference on Computing in High Energy and Nuclear Physics (CHEP 2010)*. IOP, 2011. Journal of Physics: Conference Series. doi:10.1088/1742-6596/331/3/032049.

[30] MSTW Collaboration, "Heavy-quark mass dependence in global PDF analyses and 3- and 4-flavour parton distributions", *Eur. Phys. J. C* **70** (2010) 51–72, doi:10.1140/epjc/s10052-010-1462-8, arXiv:1007.2624.

[31] H. Yoshino and V. Rychkov, "Improved analysis of black hole formation in high-energy particle collisions", *Phys. Rev. D* **71** (2005) 104028, doi:10.1103/PhysRevD.71.104028, arXiv:hep-th/0503171.

[32] H. Yoshino and V. Rychkov, "Erratum: Improved analysis of black hole formation in high-energy particle collisions", *Phys. Rev. D* **77** (2008) 089905, doi:10.1103/PhysRevD.77.089905.

[33] D. Gingrich, "Monte Carlo event generator for black hole production and decay in proton-proton collisions", *Comput. Phys. Commun.* **181** (2010) 1917–1924, doi:10.1016/j.cpc.2010.07.027, arXiv:0911.5370.

[34] CTEQ Collaboration, "Implications of CTEQ global analysis for collider observables", *Phys. Rev. D* **78** (2008) 013004, doi:10.1103/PhysRevD.78.013004, arXiv:0802.0007.

[35] P. Nicolini and E. Winstanley, "Hawking emission from quantum gravity black holes", *JHEP* **11** (2011) 075, doi:10.1007/jhep11(2011)075, arXiv:1108.4419.

[36] J. Alwall et al., "MADGRAPH/MADEVENT V4: The new web generation", *JHEP* **09** (2007) 028, doi:10.1088/1126-6708/2007/09/028, arXiv:0706.2334.

[37] GEANT4 Collaboration, "GEANT4 – a simulation toolkit", *Nucl. Instr. and Methods A* **506** (2003) 250–303, doi:10.1016/S0168-9002(03)01368-8.

[38] CMS Collaboration, "Search for Dijet Resonances in 7 TeV pp Collisions at CMS", *Phys. Rev. Lett.* **105** (2010) 211801, doi:10.1103/PhysRevLett.105.21180, arXiv:1010.0203.

[39] CMS Collaboration, "Search for Quark Compositeness with the Dijet Centrality Ratio in pp Collisions at $\sqrt{s} = 7$ TeV", *Phys. Rev. Lett.* **105** (2010) 262001, doi:10.1103/PhysRevLett.105.262001, arXiv:1010.4439.

[40] CMS Collaboration, "Measurement of Dijet Angular Distributions and Search for Quark Compositeness in pp Collisions at 7 TeV", *Phys. Rev. Lett.* **106** (2010) 201804, doi:10.1103/PhysRevLett.106.201804, arXiv:1102.2020.

[41] Particle Data Group Collaboration, "The Review of Particle Physics", *J. Phys. G* **37** (2010) 075021, doi:10.1088/0954-3899/37/7A/075021.

[42] A. L. Read, "Modified frequentist analysis of search results (The $\mathrm{CL_s}$ method)", *CERN-OPEN-2000-205* (2000).

[43] S. Park, "Critical comment on the recent microscopic black hole search at the LHC", *Phys. Lett. B* **701** (2011) 587–590, doi:10.1016/j.physletb.2011.06.039, arXiv:1104.5129.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer[1], M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka[†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, F. Teischinger, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
S. Bansal, L. Benucci, T. Cornelis, E.A. De Wolf, X. Janssen, S. Luyckx, T. Maes, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, S. Blyweert, J. D'Hondt, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, A. Olbrechts, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium
O. Charaf, B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, G.H. Hammad, T. Hreus, A. Léonard, P.E. Marage, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wickens

Ghent University, Ghent, Belgium
V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, L. Vanelderen, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, G. Bruno, L. Ceard, J. De Favereau De Jeneret, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco[2], G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrzkowski, N. Schul

Université de Mons, Mons, Belgium
N. Beliy, T. Caebergs, E. Daubie

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, S.M. Silva Do Amaral, L. Soares Jorge, A. Sznajder

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil
T.S. Anjos[3], C.A. Bernardes[3], F.A. Dias[4], T.R. Fernandez Perez Tomei, E. M. Gregores[3], C. Lagana, F. Marinho, P.G. Mercadante[3], S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
V. Genchev[1], P. Iaydjiev[1], S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, R. Hadjiiska, A. Karadzhinova, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China
J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, S. Guo, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, S. Wang, B. Zhu, W. Zou

Universidad de Los Andes, Bogota, Colombia
A. Cabrera, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia
N. Godinovic, D. Lelas, R. Plestina[5], D. Polic, I. Puljak[1]

University of Split, Split, Croatia
Z. Antunovic, M. Dzelalija, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

University of Cyprus, Nicosia, Cyprus
A. Attikis, M. Galanti, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr.

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[6], A. Ellithi Kamel[7], S. Khalil[8], M.A. Mahmoud[9], A. Radi[8,10]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
A. Hektor, M. Kadastik, M. Müntel, M. Raidal, L. Rebane, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland
V. Azzolini, P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
S. Czellar, J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
K. Banzuzi, A. Korpela, T. Tuuva

Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
D. Sillou

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, M. Marionneau, L. Millischer, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj[11], C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, S. Elgammal, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaux, C. Veelken, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram[12], J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte[12], F. Drouhin[12], C. Ferro, J.-C. Fontaine[12], D. Gelé, U. Goerlach, S. Greder, P. Juillot, M. Karim[12], A.-C. Le Bihan, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France
F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
C. Baty, S. Beauceron, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, D. Boumediene, H. Brun, J. Chasserat, R. Chierici[1], D. Contardo, P. Depasse, H. El Mamouni, A. Falkiewicz, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, T. Le Grand, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, S. Viret

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
D. Lomidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov[13]

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Ata, J. Caudron, E. Dietz-Laursonn, M. Erdmann, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, T. Klimkovich, D. Klingebiel, P. Kreuzer, D. Lanske[†], J. Lingemann, C. Magass, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
M. Bontenackels, V. Cherepanov, M. Davids, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Linn, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl, M.H. Zoeller

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz[14], A. Bethani, K. Borras, A. Cakir, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, J. Hauk, H. Jung[1], M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann[14], B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, J. Olzem, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, M. Rosin, J. Salfeld-Nebgen, R. Schmidt[14], T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, J. Tomaszewska, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
C. Autermann, V. Blobel, S. Bobrovskyi, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, N. Pietsch, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, H. Stadie, G. Steinbrück, J. Thomsen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
C. Barth, J. Berger, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, J. Gruschke, M. Guthoff[1], C. Hackstein, F. Hartmann, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov[13], J.R. Komaragiri, T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, O. Oberst, A. Oehler, J. Ott, T. Peiffer, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, M. Renz, S. Röcker, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, M. Schmanau, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, T. Weiler, M. Zeise, E.B. Ziebarth

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece
G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

University of Athens, Athens, Greece
L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou, E. Stiliaris

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas[1], P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
A. Aranyi, G. Bencze, L. Boldizsar, C. Hajdu[1], P. Hidas, D. Horvath[15], A. Kapusi, K. Krajczar[16], F. Sikler[1], G. Vesztergombi[16]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, J. Molnar, J. Palinkas, Z. Szillasi, V. Veszpremi

University of Debrecen, Debrecen, Hungary
J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

Panjab University, Chandigarh, India
S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Jindal, M. Kaur, J.M. Kohli, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, A.P. Singh, J. Singh, S.P. Singh

University of Delhi, Delhi, India
S. Ahuja, B.C. Choudhary, A. Kumar, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma, R.K. Shivpuri

Saha Institute of Nuclear Physics, Kolkata, India
S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, S. Jain, S. Jain, R. Khurana, S. Sarkar

Bhabha Atomic Research Centre, Mumbai, India
R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty[1], L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India
T. Aziz, S. Ganguly, M. Guchait[17], A. Gurtu[18], M. Maity[19], G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, A. Saha, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India
S. Banerjee, S. Dugad, N.K. Mondal

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Arfaei, H. Bakhshiansohi[20], S.M. Etesami[21], A. Fahim[20], M. Hashemi, H. Hesari, A. Jafari[20], M. Khakzad, A. Mohammadi[22], M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh[23], M. Zeinali[21]

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], L. Barbone[a,b], C. Calabria[a,b], S.S. Chhibra[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c,1], M. De Palma[a,b], L. Fiore[a], G. Iaselli[a,c], L. Lusito[a,b], G. Maggi[a,c], M. Maggi[a], N. Manna[a,b], B. Marangelli[a,b], S. My[a,c], S. Nuzzo[a,b], N. Pacifico[a,b], A. Pompili[a,b], G. Pugliese[a,c], F. Romano[a,c], G. Selvaggi[a,b], L. Silvestris[a], G. Singh[a,b], S. Tupputi[a,b], G. Zito[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], A.C. Benvenuti[a], D. Bonacorsi[a], S. Braibant-Giacomelli[a,b], L. Brigliadori[a], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,1], P. Giacomelli[a], C. Grandi[a], S. Marcellini[a], G. Masetti[a], M. Meneghelli[a,b], A. Montanari[a], F.L. Navarria[a,b], F. Odorici[a], A. Perrotta[a], F. Primavera[a], A.M. Rossi[a,b], T. Rovelli[a,b], G. Siroli[a,b], R. Travaglini[a,b]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b], G. Cappello[a,b], M. Chiorboli[a,b], S. Costa[a,b], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a,b]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], S. Frosali[a,b], E. Gallo[a], S. Gonzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], A. Tropiano[a,1]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Colafranceschi[24], F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genova, Italy
P. Fabbricatore, R. Musenich

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a,b,1], F. De Guio[a,b], L. Di Matteo[a,b], S. Fiorendi[a,b], S. Gennai[a,1], A. Ghezzi[a,b], S. Malvezzi[a], R.A. Manzoni[a,b], A. Martelli[a,b], A. Massironi[a,b,1], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], N. Redaelli[a], S. Sala[a], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli [a], Università di Napoli "Federico II" [b], Napoli, Italy
S. Buontempo[a], C.A. Carrillo Montoya[a,1], N. Cavallo[a,25], A. De Cosa[a,b], O. Dogangun[a,b], F. Fabozzi[a,25], A.O.M. Iorio[a,1], L. Lista[a], M. Merola[a,b], P. Paolucci[a]

INFN Sezione di Padova [a], Università di Padova [b], Università di Trento (Trento) [c], Padova, Italy
P. Azzi[a], N. Bacchetta[a,1], P. Bellan[a,b], D. Bisello[a,b], A. Branca[a], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], U. Dosselli[a], F. Fanzago[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], K. Kanishchev, S. Lacaprara[a,26], I. Lazzizzera[a,c], M. Margoni[a,b], M. Mazzucato[a], A.T. Meneguzzo[a,b], M. Nespolo[a,1], L. Perrozzi[a], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], M. Tosi[a,b,1], S. Vanini[a,b], P. Zotto[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
P. Baesso[a,b], U. Berzano[a], S.P. Ratti[a,b], C. Riccardi[a,b], P. Torre[a,b], P. Vitulo[a,b], C. Viviani[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
M. Biasini[a,b], G.M. Bilei[a], B. Caponeri[a,b], L. Fanò[a,b], P. Lariccia[a,b], A. Lucaroni[a,b,1], G. Mantovani[a,b], M. Menichelli[a], A. Nappi[a,b], F. Romeo[a,b], A. Santocchia[a,b], S. Taroni[a,b,1], M. Valdata[a,b]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
P. Azzurri[a,c], G. Bagliesi[a], T. Boccali[a], G. Broccolo[a,c], R. Castaldi[a], R.T. D'Agnolo[a,c], R. Dell'Orso[a], F. Fiori[a,b], L. Foà[a,c], A. Giassi[a], A. Kraan[a], F. Ligabue[a,c], T. Lomtadze[a], L. Martini[a,27], A. Messineo[a,b], F. Palla[a], F. Palmonari[a], A. Rizzi, A.T. Serban[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b,1], A. Venturi[a,1], P.G. Verdini[a]

INFN Sezione di Roma [a], Università di Roma "La Sapienza" [b], Roma, Italy
L. Barone[a,b], F. Cavallari[a], D. Del Re[a,b,1], M. Diemoz[a], C. Fanelli, D. Franci[a,b], M. Grassi[a,1], E. Longo[a,b], P. Meridiani[a], F. Micheli, S. Nourbakhsh[a], G. Organtini[a,b], F. Pandolfi[a,b], R. Paramatti[a], S. Rahatlou[a,b], M. Sigamani[a], L. Soffi

INFN Sezione di Torino [a], Università di Torino [b], Università del Piemonte Orientale (Novara) [c], Torino, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], C. Biino[a], C. Botta[a,b], N. Cartiglia[a], R. Castello[a,b], M. Costa[a,b], N. Demaria[a], A. Graziano[a,b], C. Mariotti[a,1], S. Maselli[a], G. Mazza, E. Migliore[a,b], V. Monaco[a,b], M. Musich[a], M.M. Obertino[a,c], N. Pastrone[a], M. Pelliccioni[a], A. Potenza[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], A. Solano[a,b], A. Staiano[a], A. Vilela Pereira[a]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], F. Cossutti[a], G. Della Ricca[a,b], B. Gobbo[a], M. Marone[a,b], D. Montanino[a,b,1], A. Penzo[a]

Kangwon National University, Chunchon, Korea
S.G. Heo, S.K. Nam

Kyungpook National University, Daegu, Korea
S. Chang, J. Chung, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
J.Y. Kim, Zero J. Kim, S. Song

Konkuk University, Seoul, Korea
H.Y. Jo

Korea University, Seoul, Korea
S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park, E. Seo, K.S. Sim

University of Seoul, Seoul, Korea
M. Choi, S. Kang, H. Kim, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea
Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania
M.J. Bilinskas, I. Grigelionis, M. Janulis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
M. Ahmad, M.I. Asghar, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
G. Brona, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Soltan Institute for Nuclear Studies, Warsaw, Poland
H. Bialkowska, B. Boimska, T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P. Musella, A. Nayak, J. Pela[1], P.Q. Ribeiro, J. Seixas, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia
I. Belotelov, P. Bunin, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, G. Kozlov, A. Lanev, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia
S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, A. Toropin, S. Troitsky

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov[1], A. Krokhotin, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, M. Dubinin[4], L. Dudko, A. Ershov, A. Gribushin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, L. Sarycheva[†], V. Savrin, A. Snigirev

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin[1], V. Kachanov, D. Konstantinov, A. Korablev,

V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[28], M. Djordjevic, M. Ekmedzic, D. Krpic[28], J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, C. Diez Pardos, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini[29], M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez[30], T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, C. Bernet[5], W. Bialas, G. Bianchi, P. Bloch, A. Bocci, H. Breuker, K. Bunkowski, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, B. Curé, D. D'Enterria, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, A. Gaddi, G. Georgiou, H. Gerwig, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, L. Guiducci, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, H.F. Hoffmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, P. Lenzi, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, G. Mavromanolakis, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold, M. Nguyen, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi[31], T. Rommerskirchen, C. Rovelli[32], M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas[33], D. Spiga, M. Spiropulu[4], M. Stoye, A. Tsirou, G.I. Veres[16], P. Vichoudis, H.K. Wöhri, S.D. Worm[34], W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille[35]

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, Z. Chen, A. Deisher, G. Dissertori, M. Dittmar, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, P. Lecomte, W. Lustermann,

P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli[36], P. Nef, F. Nessi-Tedaldi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, M.-C. Sawley, A. Starodumov[37], B. Stieger, M. Takahashi, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli, J. Weng

Universität Zürich, Zurich, Switzerland
E. Aguilo, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, M. Verzetti

National Central University, Chung-Li, Taiwan
Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, M. Wang

Cukurova University, Adana, Turkey
A. Adiguzel, M.N. Bakirci[38], S. Cerci[39], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, I. Hos, E.E. Kangal, G. Karapinar, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk[40], A. Polatoz, K. Sogut[41], D. Sunar Cerci[39], B. Tali[39], H. Topakli[38], D. Uzun, L.N. Vergili, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey
I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey
M. Deliomeroglu, E. Gülmez, B. Isildak, M. Kaya[42], O. Kaya[42], S. Ozkorucuklu[43], N. Sonmez[44]

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold[34], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom
L. Basso[45], K.W. Bell, A. Belyaev[45], C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Imperial College, London, United Kingdom
R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko[37], A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi[46], D.M. Raymond, S. Rogerson, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, D. Wardrope, T. Whyntie

Brunel University, Uxbridge, United Kingdom
M. Barrett, M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
K. Hatakeyama, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, USA
C. Henderson

Boston University, Boston, USA
A. Avetisyan, T. Bose, E. Carrera Jarrin, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Brown University, Providence, USA
S. Bhattacharya, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

University of California, Davis, Davis, USA
R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, M. Caulfield, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, O. Mall, T. Miceli, R. Nelson, D. Pellett, J. Robles, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra

University of California, Los Angeles, Los Angeles, USA
V. Andreev, K. Arisaka, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], J. Tucker, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA
J. Babb, R. Clare, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA
W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, H. Pi, M. Pieri, R. Ranieri, M. Sani, I. Sfiligoi, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech[47], F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA
D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi[1], V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, J.R. Vlimant, C. West

California Institute of Technology, Pasadena, USA
A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
B. Akgun, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, S.Y. Jun, Y.F. Liu, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA
J.P. Cumalat, M.E. Dinardo, B.R. Drell, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner, S.L. Zang

Cornell University, Ithaca, USA
L. Agostino, J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, W. Hopkins, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, D. Puigh, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA
A. Biselli, G. Cirino, D. Winn

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, M. Atac, J.A. Bakken, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, W. Cooper, D.P. Eartly, V.D. Elvira, S. Esen, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, H. Jensen, S. Jindariani, M. Johnson, U. Joshi, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, T. Miao, K. Mishra, S. Mrenna, Y. Musienko[48], C. Newman-Holmes, V. O'Dell, J. Pivarski, R. Pordes, O. Prokofyev, T. Schwarz, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, USA
D. Acosta, P. Avery, D. Bourilkov, M. Chen, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, S. Goldberg, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic[49], G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, M. Schmitt, B. Scurlock, P. Sellers, N. Skhirtladze, M. Snowball, D. Wang, J. Yelton, M. Zakaria

Florida International University, Miami, USA
V. Gaultney, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA
T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, S. Sekmen, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, J. Callner, R. Cavanaugh, C. Dragoiu, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, G.J. Kunde[50], F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, C. Silvestre, D. Strom, N. Varelas

The University of Iowa, Iowa City, USA
U. Akgun, E.A. Albayrak, B. Bilki[51], W. Clarida, F. Duru, S. Griffiths, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermerkaya[52], A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, J. Olson, Y. Onel, F. Ozok, S. Sen, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA
B.A. Barnett, B. Blumenfeld, S. Bolognesi, A. Bonato, C. Eskew, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, N.V. Tran, A. Whitbeck

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, G. Benelli, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, R. Stringer, G. Tinti, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, USA
A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA
J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, USA
A. Baden, M. Boutemeur, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, T. Kolberg, Y. Lu, A.C. Mignerey, A. Peterman, K. Rossato, P. Rumerio, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, USA
B. Alver, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, Y.-J. Lee, W. Li, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, USA
S.I. Cooper, P. Cushman, B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, J. Haupt, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, V. Rekovic, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Mississippi, University, USA
L.M. Cremaldi, R. Godang, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, P. Jindal, J. Keller, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, USA
U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith, Z. Wan

Northeastern University, Boston, USA
G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, USA
A. Anastassov, A. Kubik, N. Mucia, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA
L. Antonelli, D. Berry, A. Brinkerhoff, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf, J. Ziegler

The Ohio State University, Columbus, USA
B. Bylsma, L.S. Durkin, C. Hill, P. Killewald, K. Kotov, T.Y. Ling, M. Rodenburg, C. Vuosalo, G. Williams

Princeton University, Princeton, USA
N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, E. Laird, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA
J.G. Acosta, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

Purdue University, West Lafayette, USA
E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, L. Borrello, D. Bortoletto, M. De Mattia, A. Everett, L. Gutay, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA
S. Guragain, N. Parashar

Rice University, Houston, USA
A. Adair, C. Boulahouache, V. Cuplov, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, A. Garcia-Bellido, P. Goldenzweig, Y. Gotra, J. Han, A. Harel, D.C. Miner, G. Petrillo, W. Sakumoto, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA
A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

Rutgers, the State University of New Jersey, Piscataway, USA
S. Arora, O. Atramentov, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, D. Hits, A. Lath, S. Panwalkar, M. Park, R. Patel, A. Richards, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, USA
G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA
R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon[53], V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas Tech University, Lubbock, USA
N. Akchurin, C. Bardak, J. Damgov, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, P. Mane, Y. Roh, A. Sill, I. Volobouev, R. Wigmans

Vanderbilt University, Nashville, USA
E. Appelt, E. Brownson, D. Engh, C. Florez, W. Gabella, A. Gurrola, M. Issah, W. Johns, P. Kurt, C. Maguire, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA
M.W. Arenton, M. Balazs, S. Boutle, S. Conetti, B. Cox, B. Francis, S. Goadhouse, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood, R. Yohay

Wayne State University, Detroit, USA
S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, M. Mattson, C. Milstène, A. Sakharov

University of Wisconsin, Madison, USA
M. Anderson, M. Bachtis, D. Belknap, J.N. Bellinger, J. Bernardini, D. Carlsmith, M. Cepeda, S. Dasu, J. Efron, E. Friis, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

†: Deceased
1: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
2: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
3: Also at Universidade Federal do ABC, Santo Andre, Brazil
4: Also at California Institute of Technology, Pasadena, USA
5: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
6: Also at Suez Canal University, Suez, Egypt
7: Also at Cairo University, Cairo, Egypt
8: Also at British University, Cairo, Egypt
9: Also at Fayoum University, El-Fayoum, Egypt
10: Now at Ain Shams University, Cairo, Egypt
11: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
12: Also at Université de Haute-Alsace, Mulhouse, France
13: Also at Moscow State University, Moscow, Russia
14: Also at Brandenburg University of Technology, Cottbus, Germany
15: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
16: Also at Eötvös Loránd University, Budapest, Hungary
17: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
18: Now at King Abdulaziz University, Jeddah, Saudi Arabia
19: Also at University of Visva-Bharati, Santiniketan, India
20: Also at Sharif University of Technology, Tehran, Iran
21: Also at Isfahan University of Technology, Isfahan, Iran
22: Also at Shiraz University, Shiraz, Iran
23: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran
24: Also at Facoltà Ingegneria Università di Roma, Roma, Italy
25: Also at Università della Basilicata, Potenza, Italy
26: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
27: Also at Università degli studi di Siena, Siena, Italy
28: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
29: Also at University of California, Los Angeles, Los Angeles, USA
30: Also at University of Florida, Gainesville, USA
31: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
32: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
33: Also at University of Athens, Athens, Greece
34: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
35: Also at The University of Kansas, Lawrence, USA
36: Also at Paul Scherrer Institut, Villigen, Switzerland
37: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
38: Also at Gaziosmanpasa University, Tokat, Turkey

39: Also at Adiyaman University, Adiyaman, Turkey
40: Also at The University of Iowa, Iowa City, USA
41: Also at Mersin University, Mersin, Turkey
42: Also at Kafkas University, Kars, Turkey
43: Also at Suleyman Demirel University, Isparta, Turkey
44: Also at Ege University, Izmir, Turkey
45: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
46: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
47: Also at Utah Valley University, Orem, USA
48: Also at Institute for Nuclear Research, Moscow, Russia
49: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
50: Also at Los Alamos National Laboratory, Los Alamos, USA
51: Also at Argonne National Laboratory, Argonne, USA
52: Also at Erzincan University, Erzincan, Turkey
53: Also at Kyungpook National University, Daegu, Korea